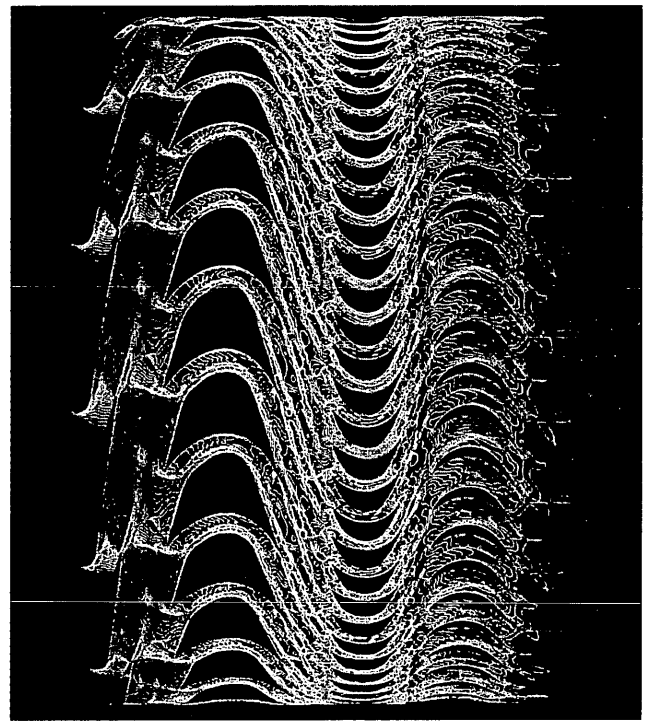
MSFC Turbine Performance Optimization (TPO) Technology Verification Status



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Introduction

- **Turbine performance optimization** → **Increased reliability**, **Higher Isp**, **Higher thrust-to-weight**

Turbine temperature, Engine Isp, Thrust-to-weight } are proportional to **Turbine efficiency**

- **Unsteady aero loads impact efficiency and life**

Capability to optimize for turbine performance and accurately predict unsteady loads will allow for increased reliability, Isp, and thrust-to-weight. The development of a fast, accurate, validated aerodynamic design, analysis, and optimization system is required.

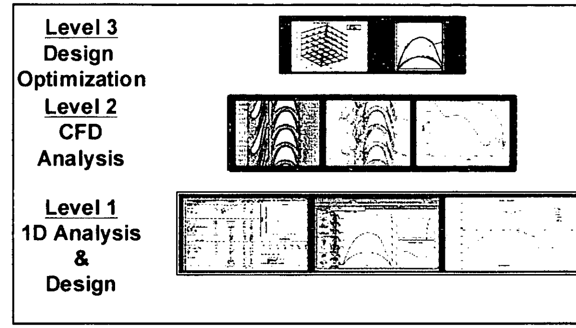
TPO Task Overall Goals and Objectives

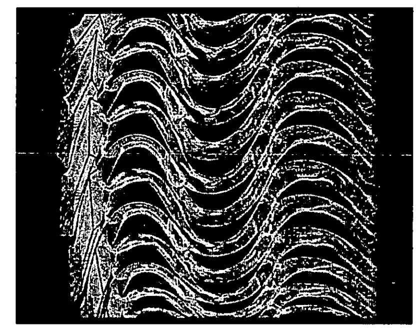
Goal: Develop and demonstrate advanced design and analysis tools for optimized turbine performance

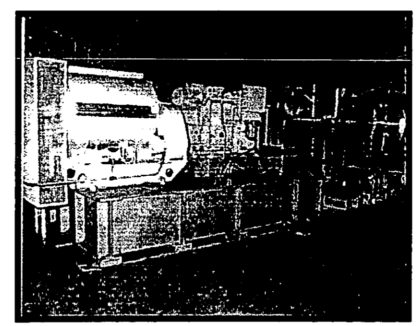
- Develop advanced turbine aerodynamic design procedure
- Apply advanced design procedure to an RLV fuel turbine to improve efficiency

Baseline η_{t-t} → + 8 points (goal)

- Verify design and analysis with testing in air at MSFC







Introduction

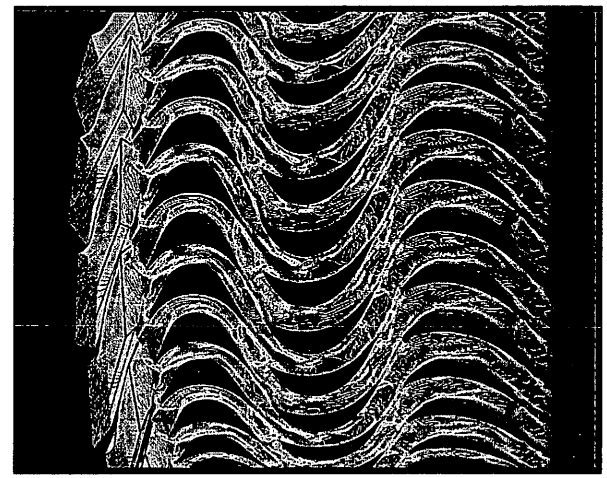
- **Both preliminary and detailed design were considered**
  - Preliminary design - diameter, speed, number of stages, areas, chords, reaction, work split
  - Detailed design - vane and blade contours
- **Task Status**
  - Preliminary design completed
  - Detailed aerodynamic design completed
  - Mechanical design of test rig completed
  - Test rig currently in manufacture
- **For this presentation, the Verification Status will be the primary focus of discussion**

Team Members

- **MSFC**
  - Meanline and CFD analysis
  - CFD code enhancement
  - Rig design and testing
  - Task management
- **Rocketdyne**
  - Aerodynamic design
  - Systems analysis
  - Test support
- **Riverbend Design Services (Frank Huber)**
  - Design code development
  - Design consultant
- **University of Florida**
  - Optimization methodology development
  - Optimization application

Background - Baseline Turbine Description

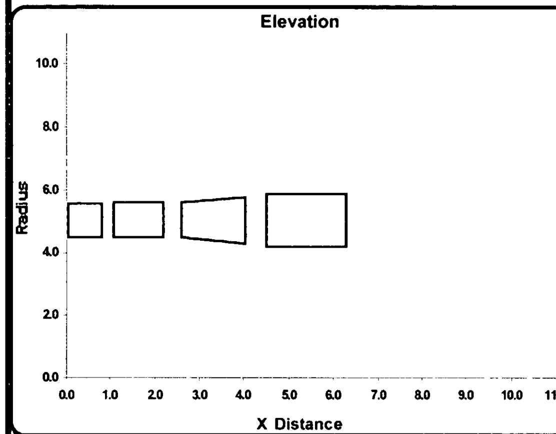
- **Design features**
  - Supersonic turbine
  - 2 stages, full admission
  - First stage
    - 21 converging-diverging, straight centerline nozzles with rectangular cross sections
    - 52 impulse, unshrouded blades
  - Second stage
    - 49 vanes
    - 42 unshrouded blades
  - Mean Diameter = 10.16 in
  - Speed = 31,396 rpm
- **Flow conditions**
  - Gaseous hydrogen/oxygen mixture, $\gamma = 1.354$
  - $P_T = 2235$, $T_o = 2235°R$, $\dot{m} = 62.04$ lbm/s
  - $Pr_{t\text{-}s} = 8.71$



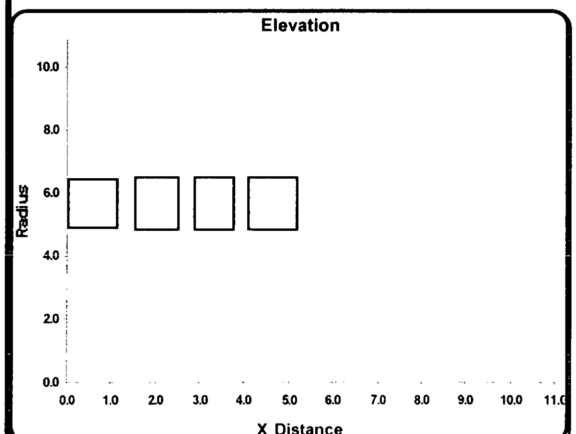
Baseline Turbine CFD Analysis

Background - Approach

- **Preliminary design**
  - Overall sizing (diameter, chords, etc.) and performance variables (speed, reaction, etc.)
- **Design process- systematic application of RSM computationally coupled to a meanline analysis**
  - Meanline Analysis
    - Predicts performance
    - Calculates gas conditions and velocity triangles
    - Generates flowpath elevation
    - Estimate of turbopump weight
    - Provides initial spanwise distribution of row exit angle
  - Meanline results used to populate the design space
  - Second order polynomials used to approximate response surface
  - Equation describing the surface interrogated to find maximum or minimum of chosen variable



Baseline



Optimized

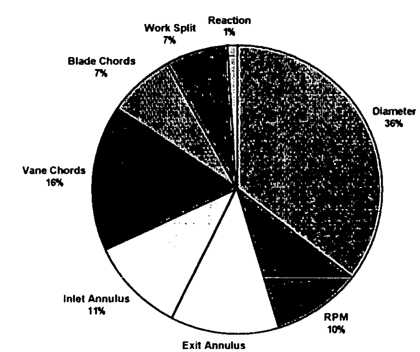
Flowpath Elevations

Background - Optimized Preliminary Turbine Description

- **Design features**
  - Supersonic turbine
  - 2 stages, full admission
  - First stage
    - 12 airfoil-type vanes
    - 30 impulse, unshrouded blades
  - Second stage
    - 73 vanes
    - 56 unshrouded blades
  - Mean Diameter = 11.4 in
  - Speed = 32,084 rpm
- **Flow conditions same as baseline**
- **Meanline predicted $\eta_{t\text{-}s}$ +9 higher than baseline**

Design Variable	Value
Mean Diameter	1.12
Speed	1.02
Exit Annulus Area	1.08
1^{st} Blade Height	1.50
1^{st} Vane Axial Chord	1.30
2^{nd} Vane Axial Chord	0.79
1^{st} Blade Axial Chord	0.71
2^{nd} Blade Axial Chord	0.62
Reaction (1^{st} Stg)	0.10
Reaction (2^{nd} Stg)	0.50
Work Fraction (1^{st} Stg)	0.90

Optimized preliminary design variables (normalized by baseline)



Effect of Variable Change on Efficiency Improvement (Percentage)

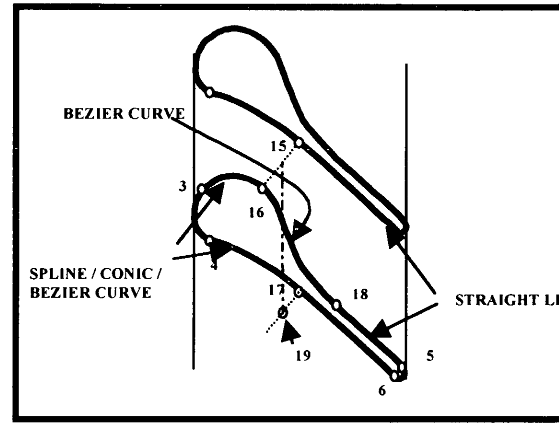
Background - Detailed Design Approach

- **A detailed design was generated for the optimized preliminary design using current design practices ⟶ INTERIM DESIGN**
- **Large number of variables made optimizing all rows simultaneously unfeasible**
- **Design process broken into two steps**
  - STEP 1: Generate and optimize the mean airfoil contours
  - STEP 2: Generate the 3D vanes and blades

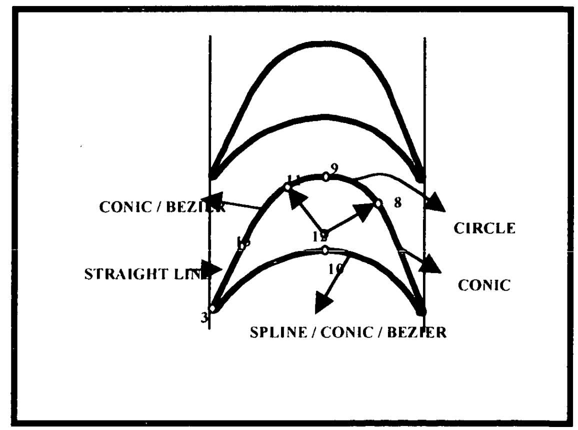
    (schedule constraints precluded performing design optimization for the 3D vanes and blades)

Background - Airfoil Contour Design Process

- **STEP 1: Choose design variables**
  - Design variables chosen as those having the most effect of the airfoil contour
- **STEP 2: Select combinations of variables to be analyzed to populate design space**
  - DOE technique, orthogonal arrays, employed
- **STEP 3: Analyze design points using quasi-3D, unsteady CFD for each stage**
  - Parametrics were performed for the vane first with the baseline blade
  - Parametrics were then performed for the first blade with the optimized blade
- **STEP 4: Train nerual nets with CFD results to augment number of design points**
- **STEP 5: Approximate the design space using polynomial-based RSM**
- **STEP 6: Find the maximum $\eta_{t\text{-}t}$ using a generalized reduced gradient method**



Nozzle Design

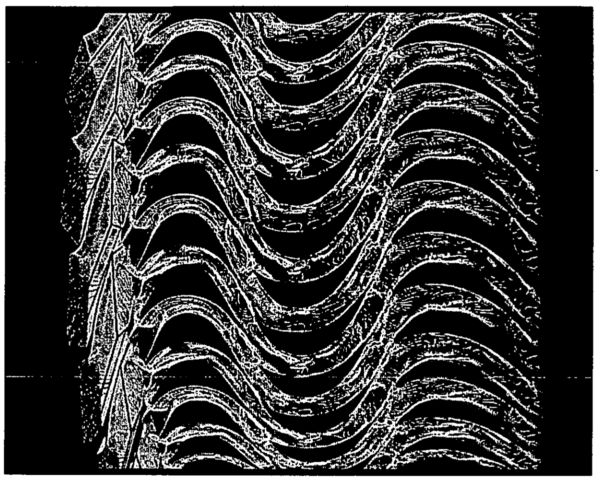


Blade Design

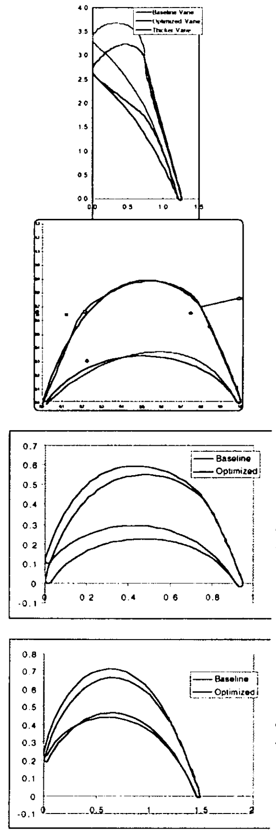
Background - 3D Design Process

- STEP 1: Stack the vanes and blades on their CGs with constant sections from hub to tip
- STEP 2: Twist blades according to free vortex distribution
- STEP 3: Perform 3D, unsteady, multistage CFD analysis of the turbine design
- STEP 4: Adjust angle distribution, sections, and stacking for improved aerodynamics

Aerodynamic Design Results - Final



Baseline CFD Analysis



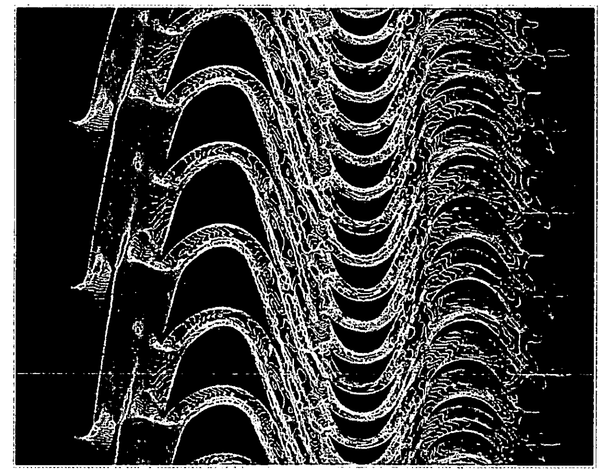
1st Vane

1st Blade

2nd Vane

2nd Blade

Optimized Blade Rows



Optimized CFD Analysis

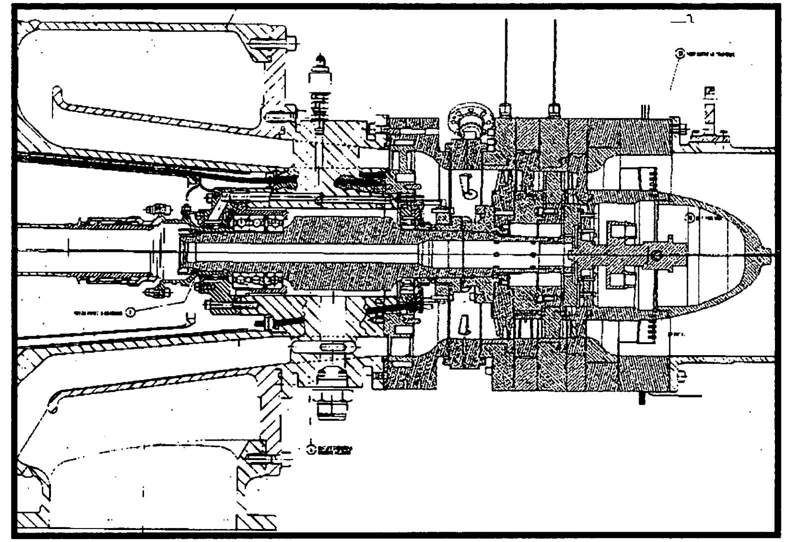
Current improvement in turbine efficiency is 11 points. This could be traded for approximately 230° R in turbine inlet temperature or ~2.25 seconds of Isp, or a combination of the two.

Test Program Objectives

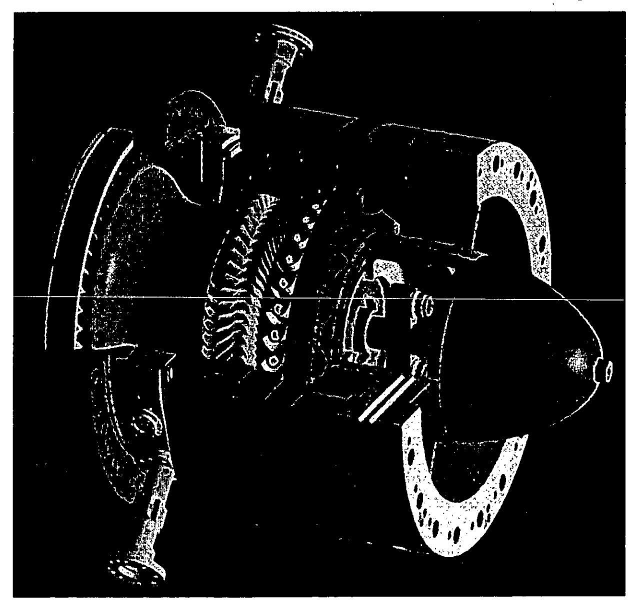
- **Verify TPO turbine design**
  - Map design and off-design performance (efficiency, flow capacity, and reaction)
  - Measure aerodynamic loads at design and off-design points (steady vane pressures, time-averaged and unsteady 1st blade pressures)
- **Verify design and analysis tools**
  - Map design and off-design efficiency
  - Measure row pressure drop
  - Measure circumferential and radial distributions of pressure, temperature, and flow angle at turbine exit
  - Measure detailed vane pressure distributions
  - Measure time-averaged and time-varying pressures on first stage blades
- **Produce detailed dataset for supersonic turbine**
- **Produce unique unsteady dataset for supersonic turbines**
  - Enhance understanding of dynamic environment in supersonic turbine
  - Provide CFD analysis validation
- **Demonstrate extended capabilities of Turbine Airflow Facility**
  - Addition of ejector for high pressure ratios

Mechanical Design

- **TPO turbine test article was designed in-house**
  - 70% scale model of the TPO to fit in the facility
- **Planned to use as much existing hardware as possible from SSME turbine rigs to reduce cost**
  - Unfortunately, rig requirements did not allow use of many existing parts
    - Bearings, slip ring, exhaust collector
- **Institued drawingless design and manufacturing process**
  - Desire to reduce design cycle/iteration time and cost
  - First project to implement this process at MSFC



Cross Section of TPO Turbine Rig



3D Solid Model of TPO Turbine Rig

Mechanical Design - Approach and Implementation

- **Data management and flow**
  - VISION: All design information stored in a database accessible by team
  - IMPLEMENTATION: EDS iMAN database was used for the management of the Computer Aid Design files providing team access to the design files
  - RESULTS: After passing the learning curve, team members had instant access to current design files for review or for use in analysis
- **Data visualization**
  - VISION: Team members will be able to access the database from their desktop computers and view all information (requirements, solid models, assembly procedures, etc.)
  - IMPLEMENTATION: EDS ProductVision used to view and mark-up files
  - RESULTS: Promising, put not trouble-free
    - After passing the learning curve, some team members used ProductVision quite successfully.
    - Because of cultural change, design reviews were not as thorough as they should have been allowing errors to persist longer than they should have
    - Unable to get ProductVision to perform fully as advertised. For example, annotations could not be viewed on the models necessitating separate note files

Mechanical Design - Approach and Implementation

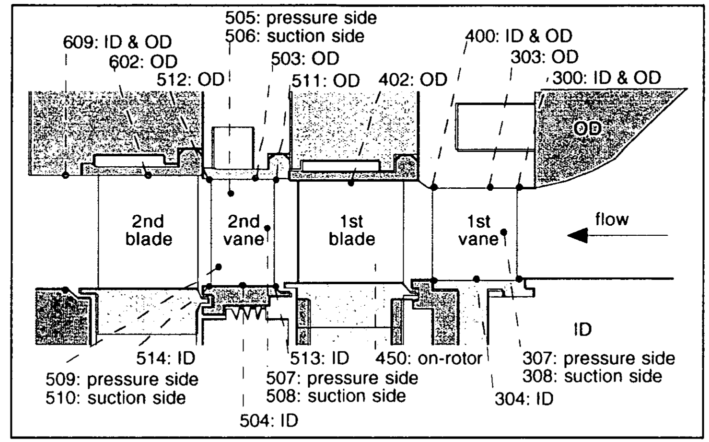
♦ Manufacturing

- VISION: Fabrication of the test article would be conducted from solid models reducing programming and inspection time and cost
- IMPLEMENTATION: Provided Unigraphics 3D solid models to fabrication vendors
- RESULTS: All results are not in yet, but results are promising
  - Vendors for the instrumented first stage rotor and for the rest of the test article were able to provide good bids
  - Manufacturing from models currently going smoothly
  - Instrumented rotor vendor reduced schedule by one month due to success with working with the models
  - At the vendor's discretion, some drawings can be made for parts that are better/more cheaply obtained

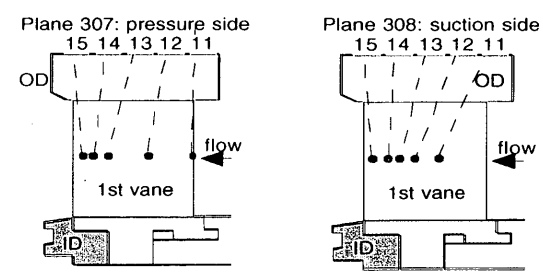
Instrumentation

- **The TPO turbine test article is highly instrumented to achieve the objectives of the test**
  - Performance
    - Total pressures and temperatures at 5 radial locations on 4 inlet struts
    - Total pressures and total temperatures on exit rotating ring.5 radial positions at 8 circumferential locations
  - Static pressure
    - Static pressure taps from upstream of strut to EGV exit at ID and OD at 8 circumferential locations
    - 1st vane pressures at 5 axial locations (pressure and suction sides) at 50% span
    - 2nd vane pressures at 5 axial locations (pressure and suction sides) at 10%, 50%, and 90% span
  - Exit flow angles
    - Probes measuring angles at locations corresponding to rake locations

Type	Total
Steady-state pressure	267
Temperature	71
Fluctuating pressures: 1^{st} stage blade / Casing	30 / 6
Accelerometers	4
Speed	2



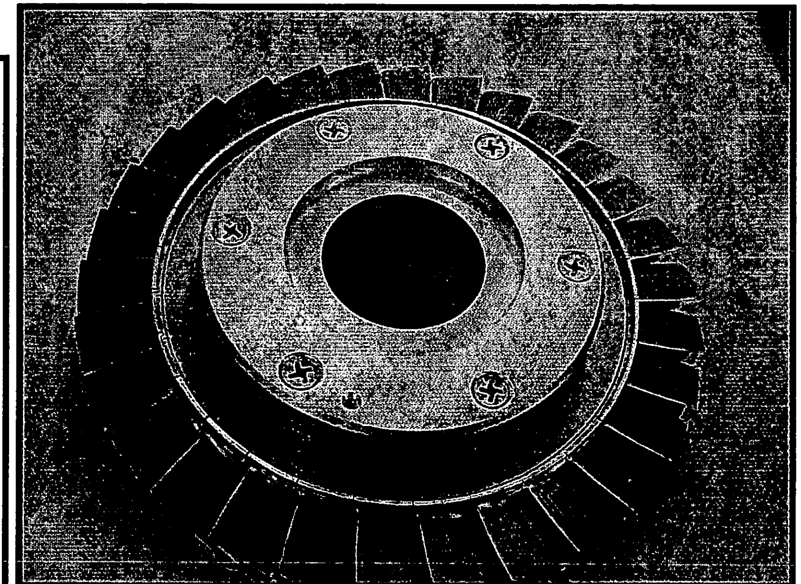
Flow Path Instrumentation Planes



1st Vane Pressure Taps @ 50% Span

Instrumentation - Fluctuating Pressures

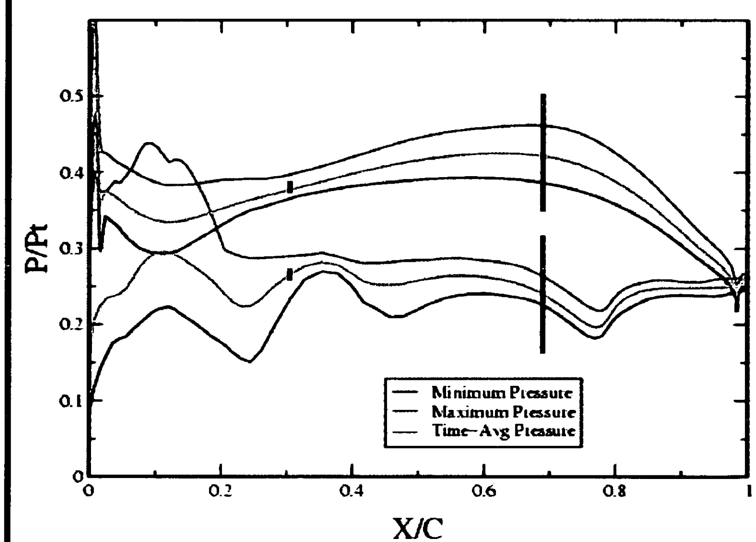
- **1st stage blades of test article instrumented with 30 Kulite semiconductor type miniature fluctuating pressure transducers**
  - Installed frequency response over 100 kHz (max 1st vane passing frequency ~ 2496 Hz)
  - Flush-mounted and epoxied into pockets on the blade surface
  - Most instrumentation concentrated at midspan with 8 transducers total at 10% and 90% span (2 axial locations each on suction and pressure surfaces)
  - Sensors distributed over 6 blades



TPO Turbine 1st Stage Blades with Inrumentation Pockets Cut into the Surfaces

Instrumentation - Fluctuating Pressures

- **Oxford University will perform extensive calibration of all surface mount pressure channels**
  - Each of 6 blades placed in pressure chamber, outputs mapped over P-T
  - Span and offset sensitivity to temperature determined
  - Blade temperature via “sense voltage” mapped for determining blade temperatures in TPO testing
  - RPM and base strain sensitivities will be evaluated via a test coupon with 2 surface mount pressures
- **Calibration information improves manufacture-quoted accuracy of 3% full-scale range to ~0.3% full-scale range**
  - This level of accuracy is CRUCIAL to effectively mapping the blade surface pressure

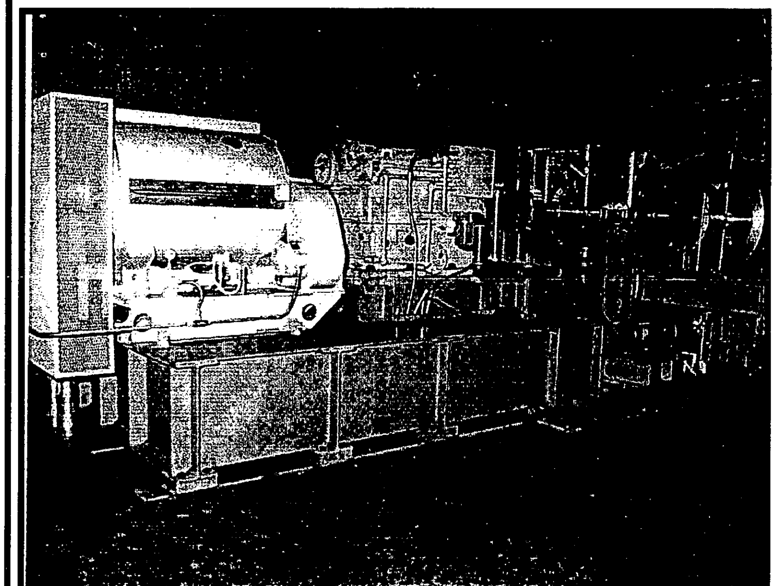


CFD Predicted 1st Blade Pressure Envelope at 50% Span.

Blue bars represent manufacturer-quoted 3% full-scale range accuracy as an error band centered on the predicted mean pressure at 70% axial chord. Pink bars at 30% span represent expected improvement attained through calibration

MSFC Turbine AirFlow Test Facility

- Blowdown facility using air (run times depend on inlet pressure and ejector)
- Regenerative thermal matrix heater
- Herschel venturi (large and small)
- Torquemeter (30, 500, and 1000 ft-lbf shafts)
- Gearbox (2:1, 1:1, and 1:2 ratios)
- Dynamometer (600 HP continuous)
- Axial or radial inflow and outflow
- Control parameters -- P_0, T_0, N, and Pr
- Exhaust to atmosphere or ejector can be used to pull vacuum pressures
  - Ejector is a new feature added to the facility
  - Checkout tests conducted November 01



MSFC Turbine AirFlow Test Facility

Test Series

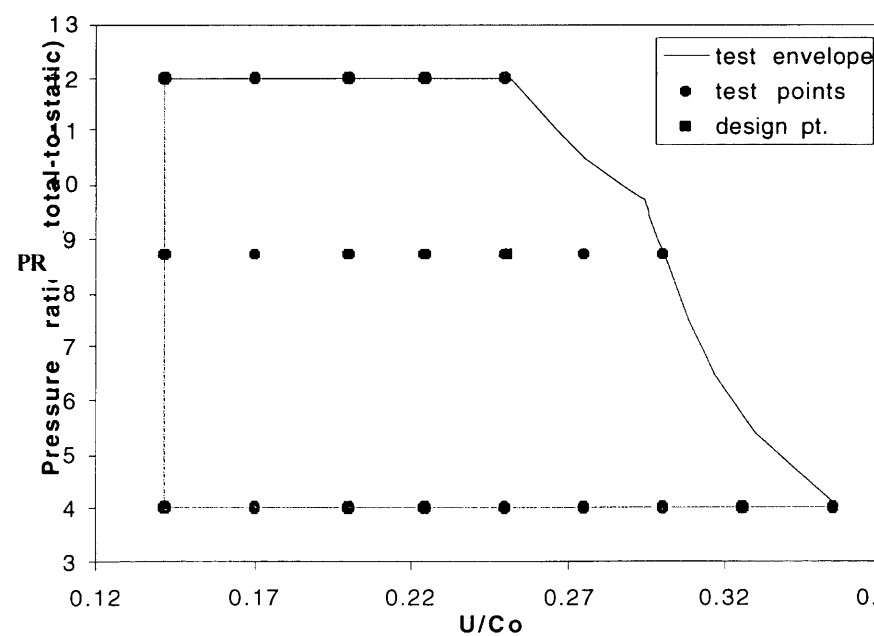
- **Series A -- In-situ tare and calibration test**
  - Measurement of torque tare due to bearing and seal losses
  - Verification of on-blade pressure transducer calibration in rotating and non-rotating environment
- **Series B -- 1st blade unsteady pressure data acquisition**
  - Performed early to reduce risk of transducer failures
- **Series C -- Steady-state performance data testing**
  - C1: Preheat evaluation
    - Determination of preheat temperature to minimize time required for temperature stabilization during critical portions of performance testing
  - C2: Exit flow angle mapping
    - Angles obtained with probes will be used to set approximate rake angles for C3
  - C3: Performance data acquisition

Test Operating Conditions and Envelope

	Parameter	Design Point	Operating Range
	Operating Fluid	air	air
	Scale	70%	70%
Control Parameters	Pressure Ratio (Total to Static)	8.71	4 to 12
	Inlet Total Temperature	300 deg F	300 deg F
	Inlet Total Pressure	70 psia	70 psia
	Speed	10,413 rpm	4950 to 12,500 rpm
Measured Parameters	Mass Flow Rate	4.2 lbm/sec	4.2 lbm/sec
	Exhaust Pressure (Total and Static)	8 psia	2 to 17.5 psia
	Exhaust Temperature (Total)	62 deg F	35 to 185 deg F
	Power	335 hp	160 to 420 hp
	Torque	169 ft-lbf	100 to 220 ft-lbf

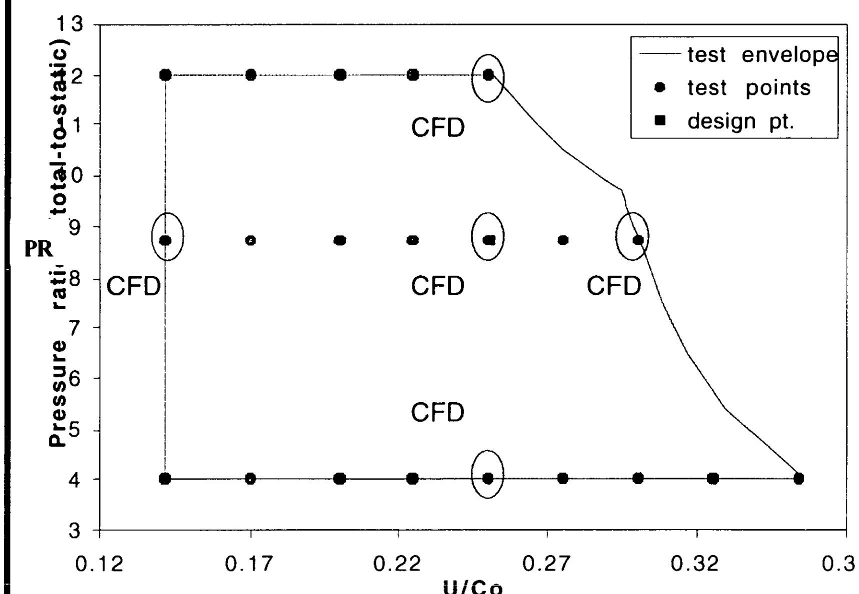
Overview of Operating Conditions

Test Envelope

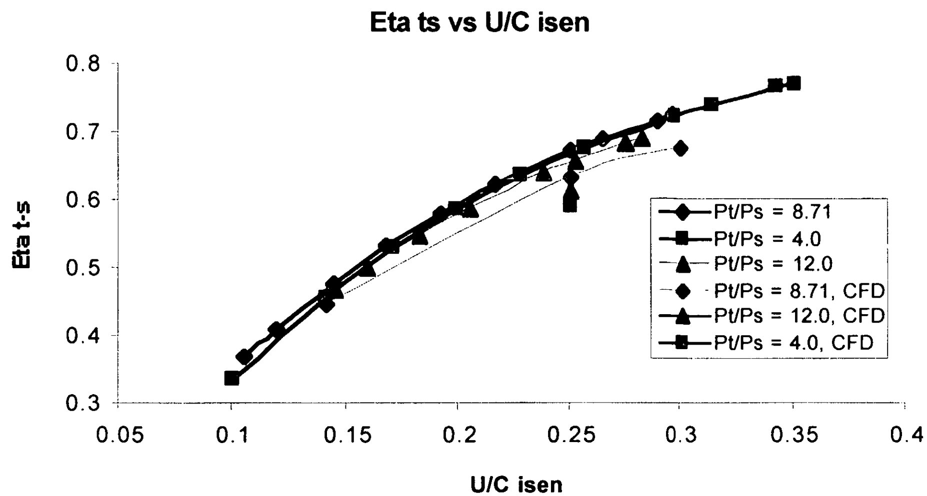


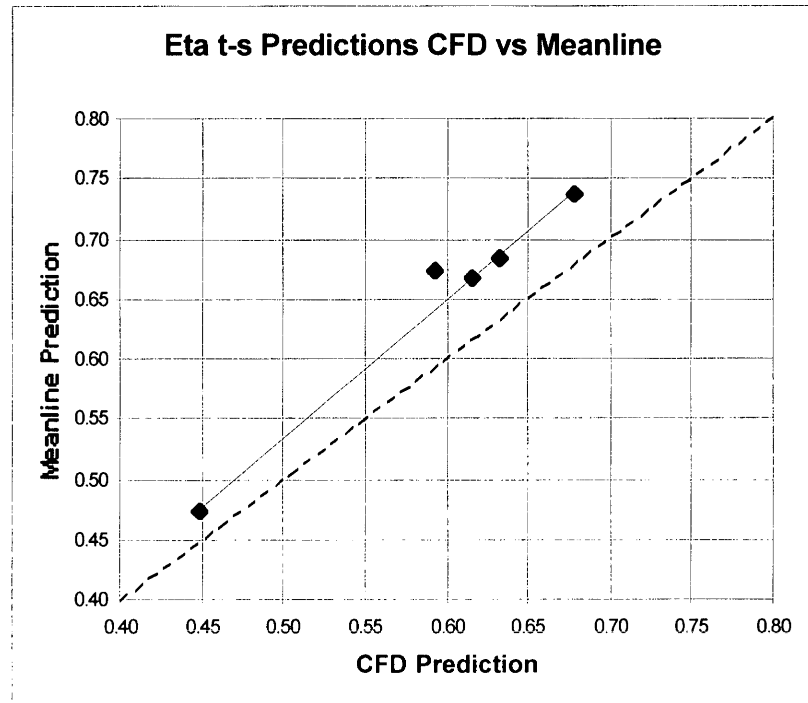
Pretest Predictions

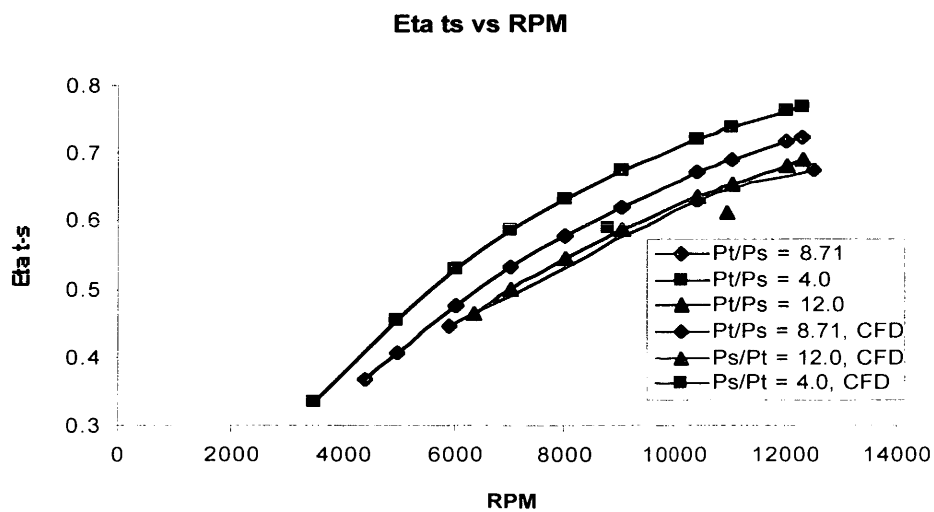
- **Meanline calculations were performed for the entire test matrix**
  - Efficiency, torque, and exit flow angle plots were provided to the test engineer
- **Unsteady CFD calculations were performed for select points in the matrix**
- **Comparisons made between meanline and CFD results**
  - Velocity triangles are similar
  - Qualitatively, the efficiency trends are similar (except at PR = 4)
  - Efficiencies are consistently predicted higher by the meanline code
  - TPO supersonic test data and CFD to be used to calibrate meanline loss model



Meanline and CFD Prediction Comparisons





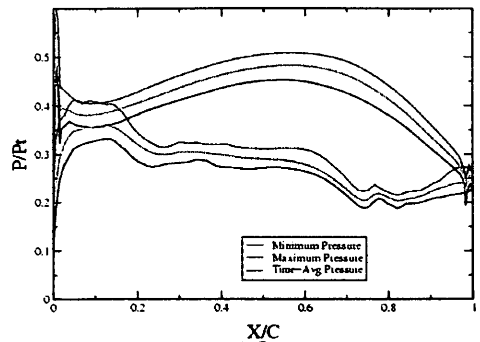


Space Transportation Directorate

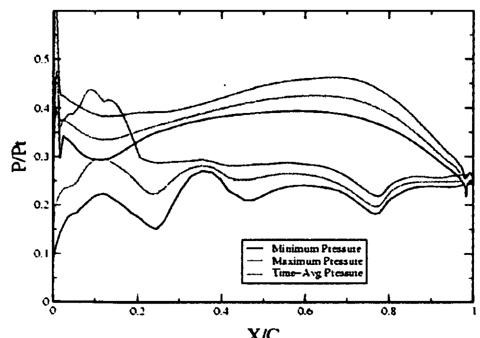
Turbine Performance Optimization

CFD Pretest Predictions

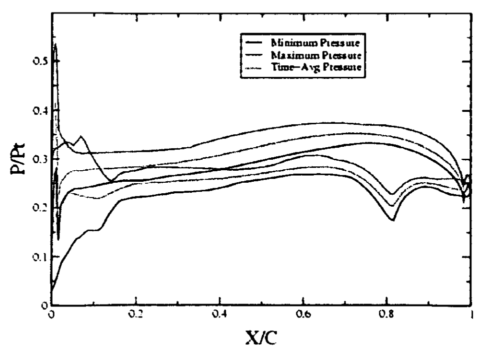
Unsteady Pressure Envelopes



90% Span

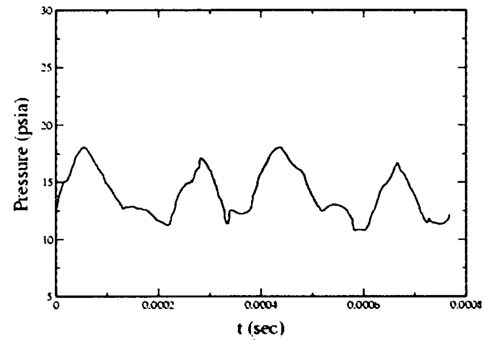


50% Span

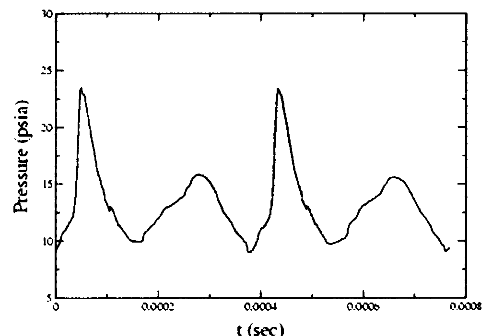


10% Span

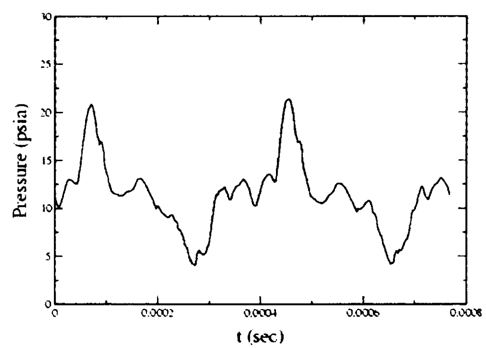
Unsteady Pressure Trace - LE



90% Span

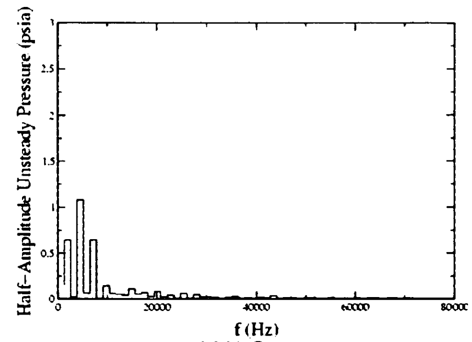


50% Span

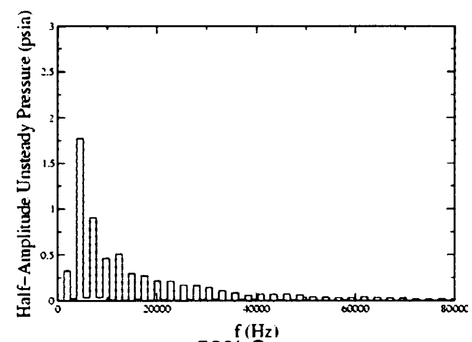


10% Span

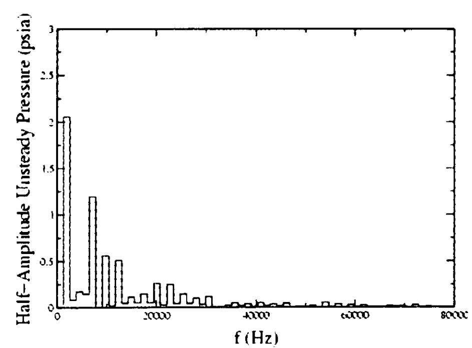
Fourier Decomposition - LE



90% Span



50% Span



10% Span

Summary

- **Successfully completed aerodynamic design and analysis phases of TPO project**
- **Implemented "drawingless" mechanical design process**
  - First implementation at MSFC
  - Implemented with varying degrees of success, but overall has been successful
- **Test article currently in fabrication**
- **Testing in air to occur in August**
  - Highly instrumented test article for detailed performance maps and code validation data
  - Fluctuating pressures on the 1st stage blades will be obtained. Extensively calibrated transducers ensure the required high degree of accuracy
  - Pretest predictions complete. Comparisons between meanline and CFD predictions are qualitatively very good and quantitatively reasonable. Meanline-predicted efficiencies consistently higher than CFD predictions
  - Unique supersonic turbine dataset will be used for design verification, code validation, and to provide insight into the flow phenomena of supersonic turbines